A WIND TUNNEL STUDY OF PEDESTRIAN
LEVEL WINDS AT THE PROPOSED
NEW ENGLAND LIFE BUILDING

WBWT-TR-1188

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THE WRIGHT BROTHERS MEMORIAL WIND TUNNEL – M.I.T.

Back Bay
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1983

Department of Aeronautics and Astronautics
Cambridge, Massachusetts

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A WIND TUNNEL STUDY OF PEDESTRIAN LEVEL WINDS AT THE PROPOSED NEW ENGLAND LIFE BUILDING

WBWT-TR-1188

submitted to

The New England Life Company
Boston, Mass.
Attn. Mr. Brian Fallon

by

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EXECUTIVE SUMMARY

Introduction

At the request of Mr. Brian Fallon of Meredith and Grew Inc., a wind tunnel study of pedestrian level winds in the vicinity of the proposed New England Life (NEL) complex near Copley Square in Boston has been carried out in the Wright Brothers Facility at the Massachusetts Institute of Technology.

Test Techniques

A. The Test

A 1-200 scale model of all buildings and open spaces within a 2000 feet radius of the proposed NEL complex was placed in an appropriately simulated flow (see Appendix B) in the wind tunnel test section. Models representing the current conditions (with the existing buildings in the NEL block) and the proposed development of the NEL block (with the new NEL complex in place) were tested using a particle erosion technique. Prior to turning on the wind the entire street level area of the model was distributed with a one particle (1 mm diameter, 2-3 mm length) thick layer. The wind was then turned on and the erosion pattern of the particle distribution was recorded photographically at several 5 mph intervals of flow velocity [measured above the model and where uninfluenced by the model (see pages 3 and 4 of the text and Appendix A for details)]. With increasing wind speed the particles are eroded away from windy areas in increasing amounts. Thus initial erosion occurs in the windiest areas at the lowest wind speeds.

B. The Data

The raw data output consists of photographs showing the patterns of eroded particles on each model for each of 12 wind directions at speeds of 0, 15, 20, 25, 30, 35 and 40 mph. 109 stations were chosen for analysis and the velocities at which the particles first eroded away were recorded for each station and direction (see Tables 1 and 2).

C. Scoring

A "score" was derived for each of the 109 stations for "Winter," "Summer" and "Storm" conditions. Using this system the results from each station were weighted according to the predominant winds during such seasons on the basis of weather records from Logan Airport. The scoring system is described in detail in the text (pages 6 and 7, and Appendix D). The "scores"

have no quantitative physical significance, but they do provide an index that allows easy comparison of the relative windiness of the many station-conditions, except as noted below under Criteria.

Criteria and Accuracy

The photographs that were used to establish the results in the absence of the NEL building model were available from another study. During that earlier study the scores from areas away from the tall buildings were averaged to find a value representative of that expected for an average corner. The score found was 1.0, and it is to be emphasized that the score represents an average for areas away from any tall buildings. Thus 1.0 is the score one might expect to be representative of a typical residential street corner in Back Bay.

Repeat data from both the earlier study and the present study typically showed that differences in score of less than 0.5 are insignificant and that differences of 0.75 are marginally significant. However, when groups of station-conditions are averaged, differences of 0.5 in average score can be significant.

Conclusions

The model study shows that the replacement of existing buildings with the proposed New England Life complex tends to reduce local winds both at the complex and in the area of blocks surrounding it. This is evidenced by the following (see Table 4):

1. 28 stations in close proximity to the proposed NEL complex were analyzed for winter, summer and storm conditions. Of the 84 possible station-conditions in the existing situation, 11 exhibited scores greater than 1.0, 6 had scores greater than 1.5, and 2 indicated scores greater than 2.0 and 2.5. No situation resulted in a score greater than 3.0. With the addition of the NEL complex only 5 had scores greater than 1.0 and none had a score greater than 1.5.

2. 81 stations in the eight blocks surrounding the proposed NEL complex were examined for the winter, summer and storm conditions, making a total of 243 station-conditions.

Replacing the existing buildings with the NEL complex resulted in the following:

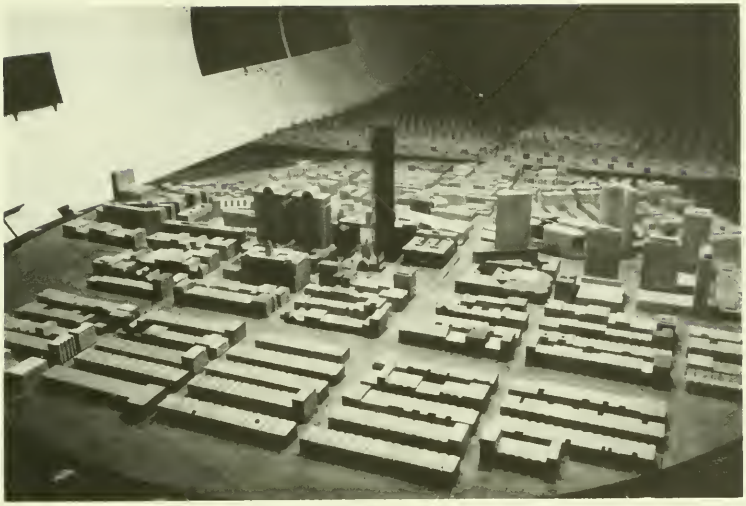
A. The number of station-conditions with scores greater than 1.0 was reduced from 126 to 98.

B. The number of station-conditions with scores greater than 1.5 was reduced from 84 to 56.

C. The number of station-conditions with scores greater than 2.0 was reduced from 44 to 23.

D. The number of station-conditions with scores greater than 2.5 was reduced from 19 to 7.

For the most part the reductions in the higher scores (greater than 1.5) occurred in the vicinity of the John Hancock tower and Trinity Church areas.



PHOTOGRAPH OF PROPOSED NEW ENGLAND LIFE
BUILDING IN THE WRIGHT BROTHERS WIND TUNNEL

CLOSE-UP OF MODEL

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I. Introduction

Tall buildings introduced into an area surrounded primarily by low buildings can sometimes cause wind conditions that adversely affect pedestrian activities. Thus it is increasingly common practice to study pedestrian level winds by means of modeling for areas that might be affected by the introduction of new structures.

At the request of Meredith and Grew Inc., acting on behalf of the New England Mutual Life Insurance Company and Gerald D. Hines Interests, such a study of pedestrian level winds in the vicinity of the proposed New England Life complex has been carried out in the Wright Brothers Facility (WBF) at the Massachusetts Institute of Technology.

The New England Life complex will occupy the entire block surrounded by Boylston and Clarendon Streets, St. James Avenue, and Berkeley Street. It will consist of two 29-story office towers surrounded by a six-story office building with retail stores on the lower floors. A parking garage will be provided under the complex.

There are numerous ways of measuring pedestrian level winds by means of tests in a wind tunnel [7]. The most common of these uses either hot wires [3,8] or pressure sensors [13] to measure the velocity at a limited number of locations in the area of interest. Use of these procedures leads to an estimate of the occurrence of winds at each station after combining wind tunnel results with a statistical description of the local wind climate [7]. A fundamental limitation of these techniques is that assumptions must be made with respect to where to make the limited number of measurements that are possible in practice.

A third possible method now in use at the WBF involves an erosion of ricelike plastic particles due to the wind. For this approach, a model of the proposed area is placed in a wind tunnel in an appropriately modeled flow (Earth's boundary layer). A single particle thick layer of the ricelike particles is placed on all pedestrian areas in the model and the test wind speed is then increased from zero to 40 mph in 5 mph intervals. The adjusted distribution of particles is recorded photographically at each speed step. The technique differs from the somewhat more conventional hot wire or pressure study in two ways: 1) the entire area is studied simultaneously since the

particles cover all pedestrian areas, and 2) the measurements correspond to only the peak gusts (at about one foot height full scale) and not the average wind (at 4 to 6 ft) which is usual basis for hot wire pressure study results. Recently this erosion technique was used in studies of the entire city of Dayton, Ohio [1], the Genessee area in Buffalo [9], and Lafayette Place in Downtown Boston [10]. It is the latter technique which was chosen for this investigation.

The wind tunnel, the model buildings and area model, etc. are described in Appendix A. The calibration of the flow in the wind tunnel is given in Appendix B, and the experimental procedures are described in Appendix C. The data and scoring system are discussed in Section II and Appendix D. The results and validation of the data are given in Section III, and the Conclusions in Section IV.

II. Photographic Data and Scoring System

The basic data from this study consists of photographs of the model showing the distribution of particles that correspond to gradient wind speeds at 5 mph intervals (i.e. the wind speed in the flow above the model and external to the simulated Earth's boundary layer) for each of 12 wind directions. In this form the data is difficult to interpret. Therefore 109 stations were chosen for analysis. Of these, 28 were in the immediate vicinity of the NEL complex and 81 were located in the eight blocks surrounding the NEL complex block. Typically during a run the erosion process clears an area of particles. The eroded area initially starts as a small spot and grows in size as the gradient wind speed is increased.

Tables 1 and 2 provide the first gradient velocity for which the photographs indicate that particles are eroded away completely from each of the 109 stations (i.e. the station became clear of particles) for each of the twelve wind directions tested. Table 1 presents the data for the test in which the NEL block contained the existing buildings (current conditions); Table 2 (proposed conditions) presents the data for the test with the proposed NEL complex in place.

In order to allow for an easier interpretation of the data as well as to emphasize those stations which are relatively windy, all 15 and 20 miles per hour entries have been squared or circled, respectively. Clearly a station that has eroded at 20 mph is windier than a station that eroded at 25 mph, etc. Different markings ($\boxed{15}$, $\textcircled{20}$) are used to emphasize these gradient velocity readings. The 109 stations chosen for analysis, as shown in Figures 1 and 2 are located as follows:

Area	Stations
I. NEL building	1 - 28
II. Block to the NE	29 - 33
III. Block to N containing existing NEL building	34 - 45, 105 - 107
IV. Block to NW	46 - 51
V. Trinity Church block	52 - 63
VI. John Hancock Tower block	64 - 78
VII. Clarendon St. JH building block	79 - 89, 108, 109
VIII. Block to SE	90 - 96
IX. Block to E	97 - 104

A relative scoring system was developed in order to evaluate the data more readily (Appendix D). The gradient velocity at which erosion first

occurred at each station for a given direction was assigned a value as follows:

Gradient Velocity (mph)	Relative Score
15	4
20	3
25	2
30	1
≥35	0

On this scale a windier station would have a higher score. A score of 4 indicates erosion of the particles at the lowest gradient wind velocity (15 mph) as compared to a station with a score of 1, say, for which erosion first occurs at a gradient velocity of 30 mph.

In order to allow an evaluation of stations for summer and winter conditions one must consider both the Boston area wind rose (Fig. 3) and the results of Table 3. The wind rose in Figure 3 indicates the percent frequency that a range of wind velocities occurred (at Logan Airport) for a given wind direction between the years 1950 and 1964. The wind rose shown includes all yearly seasons, but does not differentiate between them. It should be noted that the wind rose is strictly a record of wind conditions over a period of time. Assuming that past wind conditions are representative of future wind conditions, the wind rose is used to indicate the probability of wind speed and direction. A wind rose constructed for the winter months shows that winds occur mainly from the north, northwest and west directions with predominating northwest winds; similarly, in the summer the winds occur mainly from the west, southwest, and southerly directions, with southwest winds predominating. Furthermore, rain or snow usually occurs when the winds are from the northeast, east or southeast directions. It is also worth noting that the winds occur about one-third of the time from each of the northwest and southwest quadrants and the entire eastern half of the compass.

In order to evaluate summer, winter and storm winds, a weighted average of the above-defined scoring system was found for each season. Southwest and northwest winds are the predominating winds during the summer and winter, respectively. In storm conditions, easterly winds predominate. The weighted average for each season was defined as follows:

$$\text{Summer (SW) Average} = \frac{1}{4}\left(\frac{1}{2}\,S + SSW + SW + WSW + \frac{1}{2}\,W\right) \quad (1)$$

$$\text{Winter (NW) Average} = \frac{1}{4}\left(\frac{1}{2}\,N + NNW + NW + WNW + \frac{1}{2}\,W\right) \quad (2)$$

$$\text{Storm (E) Average} = \frac{1}{4}\left(\frac{1}{2}\,N + NE + E + SE + \frac{1}{2}\,S\right) \quad (3)$$

where S, SSW, ... are the relative scores derived from Tables 1 and 2. Such averaging was carried out for each of the two model configurations tested. The results are shown in Table 3 and summarized in Table 4.

III. Results, Validation and Error Estimates

In reviewing the photographic data there are certain criteria that are important to bear in mind when assessing the accuracy of the results. The factor that is most difficult to control from run to run is the initial spreading depth and density of the particles on the model. A one-layer thick spreading of particles should be placed on the model with consistency from run to run. Several photographs show variations in both density and thickness of the particles as spread. For those runs in which the particles were observed to have been spread either too thin or too thick initially, some account was taken in the evaluation of the results.

A second factor that cannot be controlled totally is the given gradient velocity. Although the particles and gradient velocity were allowed to stabilize after each increase in velocity, a procedural problem does exist since the nominal velocity may be exceeded during the setting procedure. The effect induced by velocity overshoot is that a higher value is recorded very quickly by the particle motion. However, errors due to such overshoot are usually quite small.

In general it is believed that these kinds of difficulties can cause errors of about one increment (5 mph) in velocity. Inconsistencies that are observed from run to run are most likely due to the above uncertainties.

For this study the comparison data used for the site with existing buildings were taken from a previous Wright Brothers Wind Tunnel test (WBWT-TR-1172A and its addendum) of pedestrian level winds at the nearby John Hancock Tower. That study used the same area model used in the NEL complex study. In addition the model was tested three times in which the only changes were landscaping in the vicinity of the John Hancock Tower. For those tests one would not expect significant change in the results away from the area of the landscaping. Thus these tests provided a source of repeat data to evaluate the effect of the uncertainties mentioned above. From those data it was concluded that a difference in score of 0.5 or less was not significant. Differences of 0.75 are marginally significant and differences in score greater than 0.75 were usually significant.

The data from the study of the pedestrian winds near the John Hancock Tower have also provided a criteria for relative windiness. The scores

from all stations significantly removed from the tall buildings were averaged to find the average score of a typical station for any condition (winter, summer, storm). That average score was 1.0 and that score has been used as the criteria in this study as well as the John Hancock study. Note that this score of 1.0 is the average many areas away from any tall building--i.e. it is the same one might expect on a typical street or corner in Back Bay.

Finally, Trinity Church Parish House at the corner of Clarendon and Boylston Streets was not included in the original model when tested for the John Hancock study. In order to determine whether the omission of that building had any significant effect on the data, the test of the existing building was repeated for six directions and the differencesin scores were computed for 54 points using data from the same six directions obtained during the original John Hancock test. The average difference in score was found to be 0.1 and the standard deviation 0.68. Further, while the photographs showed the expected changes on erosion near the left-out building, the changes in score even near the Parish House were not significant. From these comparisons it was concluded that any differences in score caused by the lack of the building extension to Trinity Church in the original test were not significant in terms of the expected accuracy.

IV. Conclusions

A wind erosion study of the proposed New England Life complex has been carried out to determine the effect of the proposed complex on pedestrian level winds near the building and in the surrounding area. A model depicting the entire area within a 2000 foot radius of the site has been tested in an appropriately simulated Earth's boundary layer in the wind tunnel. Tests were conducted both with the existing buildings and the proposed NEL complex in place in the NEL block.

The primary data from this study are photographs of the model showing the erosion of ricelike particles caused by the wind at stepped intervals of 5 mph from 12 wind directions. To facilitate interpretation of the photographs a relative scoring system was defined and used to evaluate 109 stations, 28 of which were in the immediate vicinity of the NEL complex. In a previous study it was found that in the scoring system a score of 1.0 was a reasonable divider point between windy and non-windy areas (based on an average for a typical station at a distance from any tall building). Also from that study and the current study it was found that when comparing stations differences in scores of 0.5 or less were insignificant (i.e. were within the error tolerance of the data).

It is concluded from an examination of all results of the test that replacing the existing building with the NEL complex in the model tested had the net effect of reducing the pedestrian level winds both in the near proximity and at reasonable distances away from the NEL complex. This tendency to reduce the wind in and around the NEL complex is evidenced as follows.

Each of the 109 stations was evaluated for winter, summer and storm conditions, for a total of 327 station conditions. Of the 84 station-conditions (28 stations - 3 conditions each) considered in the immediate vicinity of the NEL complex, 11 showed scores greater than unity with the existing buildings in place, whereas only 5 had scores greater than 1.0 with the NEL complex in place. Also of significance is the fact that of the original 11 station-conditions, 10 indicated scores greater than 1.5 whereas none of the 5 with the NEL complex exceeded 1.5. Further, for the 245 station-conditions in eight blocks surrounding the NEL complex, 132

were greater than 1.0 with the existing buildings, whereas only 103 were greater than 1.0 with the NEL complex in place. Those with scores greater than 1.5 were reduced from 88 to 5, greater than 2.0 from 47 to 23, and greater than 2.5 from 21 to 7. The reductions of the higher scores were particularly noticeable in the vicinity of the John Hancock Tower and Trinity Church.

Table 1. Current Conditions

Gradient Velocities for First Erosion at Selected Ground Wind Stations

STATION AREA I	N	NE	E	SE	S	SSW	SW	WSW	W	WNW	NW	NNW	N
	NEW ENGLAND LIFE BUILDING												
1	25	25	25	30	40	35	25	40	40	35	35	25	25
2	25	35	35	35	40	35	25	40	40	40	40	25	25
3	25	30	35	35	40	35	25	40	40	40	40	25	25
4	25	30	35	35	40	35	25	40	40	40	40	25	25
5	25	(20)	25	25	40	30	30	40	40	40	40	35	25
6	40	35	30	30	40	30	30	35	35	35	35	25	40
7	40	35	30	30	40	30	30	35	35	35	35	25	40
8	40	35	30	30	40	30	30	35	30	35	35	25	40
9	30	40	35	40	35	(20)	(20)	25	(20)	25	30	25	30
10	30	40	40	30	30	30	(20)	25	(20)	25	30	40	30
11	40	35	35	40	30	[15]	[15]	25	25	25	35	40	40
12	40	35	35	**40**	**40**	40	25	30	25	25	35	**40**	40
13	**40**	35	35	40	40	35	35	45	40	35	35	40	**40**
14	35	35	40	40	40	(20)	25	40	40	40	35	35	35
15	35	35	25	30	30	35	40	40	40	35	35	35	35
16	35	35	25	25	(20)	(20)	25	40	40	30	35	30	35
17	35	40	35	25	(20)	(20)	25	40	40	35	35	35	35
18	35	40	(20)	25	(20)	25	30	**40**	**40**	**40**	40	30	35
19	35	30	40	40	25	25	35	35	40	40	40	30	35
20	40	30	**40**	40	40	35	(20)	40	40	35	35	30	40

STATION	N	NE	E	SE	S	SSW	SW	WSW	W	WNW	NW	NNW	N
AREA II Block to the NE													
29	40	40	40	25	25	(20)	40	25	25	40	40	40	40
30	40	40	30	25	40	25	(20)	25	(20)	(20)	(20)	25	40
31	40	40	30	25	40	25	(20)	25	25	(20)	(20)	25	40
32	40	40	40	40	40	35	30	25	30	(20)	30	30	40
33	30	35	40	40	40	35	35	25	25	(20)	25	30	30
AREA III Existing NEL Building Block													
34	(20)	30	25	35	40	40	40	40	35	30	(20)	30	(20)
35	40	25	30	30	40	40	40	40	40	40	35	30	40
36	40	30	25	30	40	40	35	40	40	40	35	30	40
37	35	(20)	(20)	30	25	30	25	30	40	35	40	25	35
38	40	(20)	(20)	25	20	25	25	40	40	40	45	30	40
39	40	35	25	(20)	(20)	25	(20)	40	40	40	40	40	40
40	40	40	30	25	25	[15]	25	25	30	30	30	40	40
41	40	40	35	30	35	25	25	25	(20)	(20)	(20)	30	40
42	(20)	40	30	35	35	(20)	(20)	(20)	(20)	25	30	25	(20)
43	(20)	30	40	40	40	30	(20)	25	(20)	(20)	(20)	(20)	(20)
44	[15]	25	40	40	35	25	(20)	(20)	[15]	[15]	(20)	[15]	[15]
45	30	35	30	40	40	40	40	40	30	30	30	25	30
105	30	30	25	30	40	40	40	40	40	35	35	30	30
106	(20)	30	25	30	40	40	40	40	40	40	30	25	(20)
107	[15]	25	(20)	(20)	40	40	40	40	40	40	30	25	[15]

STATION	N	NE	E	SE	S	SSW	SW	WSW	W	WNW	NW	NNW	
AREA IV Block to NW													
46	25	25	25	30	30	25	25	30	30	35	35	25	25
47	40	30	(20)	(20)	40	30	30	35	30	30	30	30	40
48	40	40	25	30	30	(20)	25	35	30	30	35	35	40
49	40	40	40	25	(20)	25	40	40	40	40	40	40	40
50	40	40	25	25	[15]	(20)	30	(20)	30	25	30	40	40
51	40	40	30	25	[15]	(20)	30	25	(20)	25	(20)	(20)	40
AREA V Trinty Church Block													
52	45	30	(20)	45	35	(20)	40	30	30	30	(20)	30	40
53	35	40	35	40	25	25	30	40	35	35	30	40	35
54	35	35	25	40	25	[15]	25	35	35	35	30	30	40
55	40	40	40	40	30	(20)	30	40	35	35	40	40	40
56	40	40	40	40	35	30	30	35	40	35	40	40	40
57	40	40	40	40	35	30	30	35	40	35	40	40	40
58	30	30	30	30	40	(20)	(20)	30	25	30	35	35	30
59	35	25	30	40	40	35	25	30	25	30	35	40	40
60	30	(20)	(20)	(20)	35	40	35	30	30	35	35	30	40
61	30	25	(20)	25	30	(20)	(20)	(20)	25	30	30	30	30
62	25	25	(20)	30	(20)	[15]	(20)	25	30	30	35	30	25
63	40	40	40	40	25	[15]	(20)	25	(20)	30	25	35	40

Note UNDER PROPOSED CONDITIONS, WIND DECREASED SEE PG 28. WHY ?

AREA VI John Hancock Tower Block

STATION	N	NE	E	SE	S	SSW	SW	WSW	W	WNW	NW	NNW	N
64	20	25	30	40	25	15	15	15	25	20	15	20	20
65	20	20	15	40	25	15	15	20	25	25	20	15	20
66	20	20	15	35	30	20	20	20	15	20	20	15	20
67	30	20	25	30	35	40	25	35	20	15	20	15	30
68	25	20	15	35	35	40	30	20	15	25	20	20	25
69	25	15	20	25	30	35	35	25	25	30	25	25	25
70	35	20	30	40	35	20	25	30	30	30	30	30	35
71	25	20	20	35	25	35	35	35	30	35	30	30	25
72	30	20	35	30	30	20	35	30	40	40	35	30	30
73	25	20	20	25	25	40	35	40	40	40	35	30	25
74	25	15	25	15	20	25	35	30	35	40	35	20	25
75	30	15	25	20	15	15	15	25	15	30	40	35	30
76	30	25	30	25	25	25	25	35	30	35	40	35	30
77	30	35	30	25	30	30	30	35	20	25	30	30	30
78	25	35	25	30	35	30	25	30	20	20	25	30	25

STATION	N	NE	E	SE	S	SSW	SW	WSW	W	WNW	NW	NNW	N
AREA VII Clarendon St. JH Building Block													
79	35	40	35	25	(20)	25	25	30	30	(20)	35	35	35
80	25	(20)	35	25	(20)	[15]	[15]	25	30	25	30	25	25
81	30	30	35	40	35	30	35	30	25	25	40	25	30
82	35	40	40	40	40	40	35	30	30	25	25	25	35
83	35	40	40	40	40	40	40	40	40	35	40	35	35
84	(20)	35	35	25	[15]	35	(20)	35	35	30	30	(20)	(20)
85	30	30	35	(20)	[15]	25	30	40	35	25	30	25	30
86	40	35	30	35	30	30	40	40	40	35	40	35	40
87	30	35	(20)	(20)	(20)	[15]	30	40	35	(20)	25	30	30
88	40	40	25	25	[15]	(20)	25	40	40	40	40	40	40
89	40	45	25	**30**	**30**	**30**	30	40	**40**	30	40	40	40
108	30	30	35	40	25	(20)	25	40	30	30	40	**40**	30
109	35	35	35	30	(20)	(20)	(20)	25	40	40	30	**40**	35
AREA VIII Block to SE													
90	40	40	25	(20)	35	40	30	40	**40**	40	30	35	40
91	35	25	40	35	(20)	(20)	25	25	35	(20)	25	(20)	35
92	35	25	40	35	(20)	(20)	25	25	35	(20)	25	(20)	35
93	35	35	25	40	(20)	(20)	(20)	25	30	(20)	(20)	25	35
94	30	40	(20)	30	25	25	(20)	35	30	(20)	25	25	30
95	30	40	25	30	25	25	(20)	35	30	(20)	25	25	30
96	35	25	40	30	25	35	40	40	30	25	30	25	35

STATION AREA IX	N Block	NE to E	E	SE	S	SSW	SW	WSW	W	WNW	NW	NNW	
97	35	35	30	(20)	(20)	(20)	35	40	40	40	40	35	35
98	40	40	30	25	(20)	25	25	25	(20)	(20)	35	30	40
99	40	40	35	25	(20)	25	25	25	(20)	(20)	35	30	40
100	25	35	40	40	25	30	40	30	25	30	30	(20)	25
101	40	40	40	40	35	40	40	40	40	30	35	25	40
102	40	30	40	[15]	35	25	30	35	35	30	30	30	40
103	40	30	40	[15]	35	25	35	35	35	30	30	30	40
104	40	25	40	40	40	40	40	40	40	40	35	30	40

Table 2. Proposed Conditions

Gradient Velocities for First Erosion at Selected Ground Wind Stations

STATION	N	NE	E	SE	S	SSW	SW	WSW	W	WNW	NW	NNW	N
AREA I NEW ENGLAND LIFE BUILDING													
1	30	40	25	40	35	40	40	40	40	40	30	40	30
2	30	40	40	40	40	40	35	40	40	35	30	30	30
3	35	35	40	40	40	40	35	40	40	40	30	35	35
4	35	35	40	40	40	35	35	40	40	40	40	40	35
5	40	30	40	40	40	35	35	40	40	40	40	40	40
6	30	40	40	40	40	35	35	40	40	30	30	30	30
7	30	40	40	40	40	30	35	40	40	40	30	30	30
8	20	30	40	40	40	35	30	40	40	35	35	30	20
9	30	35	40	35	40	30	20	25	40	35	40	40	30
10	35	35	40	35	40	30	20	35	30	30	40	40	35
11	35	30	35	35	40	40	20	35	30	25	40	40	35
12	30	30	35	30	25	30	30	35	25	20	35	35	30
13	30	30	40	25	20	25	35	35	30	30	30	30	30
14	30	35	40	40	25	35	35	40	30	30	30	35	30
15	40	40	40	35	25	40	40	40	30	30	30	35	40
16	40	35	35	30	30	35	40	40	40	35	35	35	40
17	30	35	30	30	30	35	40	40	40	40	35	35	30
18	30	35	30	30	25	30	40	40	40	40	30	30	30
19	35	35	30	35	30	35	40	40	40	35	30	35	35
20	40	40	35	35	30	40	40	40	35	35	30	40	40
21	35	40	40	40	40	40	40	40	40	30	25	30	35
22	35	35	40	40	40	40	40	40	40	30	25	30	35
23	35	35	40	40	40	40	40	40	40	40	35	35	35
24	35	40	40	40	40	40	40	40	40	35	30	30	35
25	30	40	40	40	40	40	40	40	35	30	30	30	30
26	30	35	40	40	40	40	40	40	40	30	30	25	30
27	30	30	40	40	40	40	40	40	40	40	35	35	30
28	35	40	40	40	40	40	40	40	40	35	30	30	35

STATION	N	NE	E	SE	S	SSW	SW	WSW	W	WNW	NW	NNW	N
AREA II Block to NE													
29	40	40	40	25	40	40	40	40	40	40	35	40	40
30	40	40	35	35	30	40	25	30	40	35	(20)	35	40
31	40	40	35	35	35	40	25	30	40	35	25	30	40
32	40	40	40	40	35	40	30	30	40	40	30	30	40
33	35	40	40	40	40	40	35	30	30	30	30	30	35
AREA III Present NEL Building													
34	35	30	35	30	35	40	40	40	40	40	30	30	35
35	40	30	35	30	35	40	40	40	40	40	40	40	40
36	35	30	40	25	35	40	40	40	40	40	40	35	35
37	35	30	25	25	35	40	35	40	40	40	40	40	35
38	40	25	(20)	25	(20)	40	25	40	40	40	40	40	40
39	40	40	35	40	(20)	30	35	40	40	40	40	40	40
40	30	40	35	35	35	25	25	25	25	25	30	25	30
41	30	40	35	35	35	25	25	30	25	25	30	25	30
42	30	40	40	40	35	35	(20)	25	35	25	25	35	30
43	30	35	40	40	35	35	25	25	25	30	30	35	30
44	30	35	40	40	35	35	25	25	25	30	30	35	30
45	35	35	35	40	35	40	40	40	40	40	35	35	35
105	35	30	25	35	35	40	40	40	40	40	40	40	35
106	30	30	(20)	40	35	40	40	40	40	40	35	30	30
107	30	25	(20)	30	35	40	40	40	40	40	25	25	30

STATION	N	NE	E	SE	S	SSW	SW	WSW	W	WNW	NW	NNW	N
AREA IV Block to NW													
46	30	30	25	40	35	35	25	25	30	25	35	30	30
47	30	30	25	30	40	25	30	30	30	30	30	30	30
48	30	35	25	30	35	(20)	25	40	35	35	35	30	30
49	40	40	40	35	(20)	30	40	40	40	40	40	40	40
50	40	40	40	25	(20)	25	35	25	25	25	30	40	40
51	35	40	40	30	[15]	25	35	35	25	25	30	40	35
AREA V TRINITY CHURCH													
52	40	40	40	40	25	30	40	40	40	30	30	40	40
53	35	40	35	40	(20)	25	30	40	40	35	35	40	35
54	40	40	40	40	30	25	25	35	40	40	30	40	40
55	40	40	35	40	30	25	30	40	40	35	40	40	40
56	35	40	40	40	40	30	30	40	40	40	40	40	35
57	30	40	40	40	40	30	30	40	40	40	40	40	30
58	(20)	25	35	35	35	35	25	35	25	25	35	40	(20)
59	(20)	(20)	25	30	(20)	25	40	40	30	35	35	30	(20)
60	25	(20)	25	25	25	30	40	30	30	30	25	25	25
61	30	25	25	25	35	30	(20)	25	30	30	25	25	30
62	30	25	(20)	(20)	35	(20)	(20)	25	35	35	30	30	30
63	35	40	40	40	30	(20)	25	25	35	40	40	40	35

STATION AREA VI	N JOHN	NE HANCOCK	E	SE TOWER	S	SSW	SW	WSW	W	WNW	NW	NNW	N
64	20	25	25	30	30	20	20	20	30	30	25	20	20
65	20	25	25	30	30	20	20	20	30	30	25	20	20
66	25	25	20	20	35	30	30	25	25	20	20	20	25
67	25	25	20	20	35	30	30	25	25	20	20	20	25
68	25	20	25	30	25	25	40	25	30	30	25	20	25
69	25	20	25	40	20	20	40	35	30	30	30	30	25
70	30	20	25	30	30	35	40	25	30	30	25	25	30
71	30	20	25	40	30	30	25	40	30	35	30	30	30
72	30	20	20	40	25	35	40	35	35	40	30	30	30
73	30	20	25	40	20	20	25	40	40	35	30	30	30
74	20	20	20	25	15	20	20	25	25	30	30	25	20
75	20	20	20	20	15	20	20	25	25	30	30	25	20
76	30	30	35	20	25	25	20	30	30	30	35	35	30
77	30	40	30	20	30	25	30	35	25	20	30	25	30
78	30	40	30	20	30	25	30	35	25	20	30	25	30

STATION AREA VII	N	NE CLARENDON	E ST	SE BUILDING	S	SSW	SW	WSW	W	WNW	NW	NNW	N
79	(20)	(20)	25	25	(20)	25	25	25	25	(20)	25	25	(20)
80	(20)	(20)	25	25	(20)	20	(20)	25	25	25	25	25	(20)
81	(20)	25	35	25	(20)	25	30	30	25	25	35	30	(20)
82	(20)	30	35	25	(20)	25	30	30	25	25	25	25	(20)
83	25	30	40	30	(20)	40	40	40	30	30	25	30	25
84	35	(20)	35	30	25	30	35	40	40	40	30	30	35
85	35	25	35	30	25	25	30	40	40	40	30	30	35
86	35	30	35	40	30	25	30	40	40	40	40	35	35
87	40	25	30	30	25	25	25	40	40	40	40	40	40
88	40	25	40	30	25	25	30	40	40	40	40	40	40
89	40	30	40	30	25	30	35	40	40	40	40	40	40
107	30	25	30	30	(20)	(20)	(20)	30	40	30	35	40	30
108	30	25	30	40	30	(20)	(20)	40	35	30	40	35	30

STATION	N	NE	E	SE	S	SSW	SW	WSW	W	WNW	NW	NNW	N
AREA VIII	Block to SE												
90	40	40	40	30	35	40	40	40	40	40	40	40	40
91	40	40	40	40	30	30	25	35	40	40	40	40	40
92	40	30	35	40	30	30	25	35	40	40	40	40	40
93	30	40	35	40	30	25	(20)	35	40	40	35	30	30
94	30	40	30	35	(20)	30	30	40	40	35	25	(20)	30
95	30	40	35	35	25	30	35	40	40	35	25	(20)	30
96	35	30	35	40	(20)	35	40	40	40	40	35	30	35
AREA IX	Block to E												
97	40	40	40	30	25	25	35	40	40	40	40	40	40
98	30	40	40	35	25	30	35	40	40	30	(20)	(20)	30
99	(20)	40	40	35	25	30	35	40	40	25	(20)	(20)	(20)
100	30	40	40	35	25	35	40	40	35	25	(20)	25	30
101	40	40	40	40	40	40	40	40	40	30	30	35	40
102	40	35	35	35	30	40	25	40	35	(20)	25	40	40
103	40	35	35	35	35	40	40	35	40	30	25	40	40
104	40	40	40	40	40	40	40	40	40	40	40	40	40

Table 3. RELATIVE SCORES FOR SELECTED GROUND WIND STATIONS IN WINTER, SUMMER, AND STORM SEASONS - ORIGINAL AND NEL BUILDINGS MODELS

STATION AREA I	WINTER (NW) ORIG	WINTER (NW) NEL	SUMMER (SW) ORIG	SUMMER (SW) NEL	STORM (E) ORIG	STORM (E) NEL
	NEW ENGLAND LIFE					
1	0.50	0.38	0.25	0.00	0.50	0.63
2	0.75	0.63	0.50	0.00	0.25	0.13
3	0.75	0.25	0.50	0.00	0.50	0.00
4	0.75	0.00	0.50	0.00	0.50	0.00
5	0.13	0.00	0.00	0.00	0.13	0.25
6	0.50	0.88	0.50	0.00	0.50	0.13
7	0.50	0.63	0.50	0.25	0.50	0.63
8	0.63	0.63	0.63	0.25	0.50	0.63
9	1.13	0.13	1.63	1.50	0.00	0.13
10	1.25	0.38	2.88	1.13	0.13	0.00
11	0.75	0.63	2.88	0.88	0.13	0.25
12	0.75	1.13	1.00	1.00	0.00	0.88
13	0.00	1.00	0.00	1.00	0.00	1.25
14	0.00	0.75	1.25	0.38	0.00	0.38
15	0.00	0.63	0.13	0.38	0.88	0.25
16	0.50	0.00	1.63	0.13	1.38	0.38
17	0.00	0.13	1.63	0.13	0.88	0.75
18	0.25	0.63	1.13	0.50	1.63	0.88
19	0.25	0.25	0.75	0.13	0.50	0.38
20	0.25	0.25	0.75	0.13	0.25	0.13
21	*	1.00	*	0.00	*	0.00
22	*	1.00	*	0.00	*	0.00
23	*	0.00	*	0.00	*	0.00
24	*	0.50	*	0.00	*	0.00
25	*	0.88	*	0.00	*	0.13

STATION	WINTER (NW) ORIG	NEL	SUMMER (SW) ORIG	NEL	STORM (E) ORIG	NEL
26	*	1.13	*	0.00	*	0.13
27	*	0.13	*	0.00	*	0.38
28	*	0.50	*	0.00	*	0.00

* These stations are located in the enclosed plaza areas of the proposed New England Life Building. As a result these stations do not exist in the original model, where a parking facility is presently located.

STATION		WINTER (NW) ORIG	NEL	SUMMER (SW) ORIG	NEL	STORM (E) ORIG	NEL
AREA II	Block to NE						
29		0.25	0.00	1.75	0.00	0.75	0.50
30		2.38	0.75	2.13	0.88	0.75	0.13
31		2.25	0.75	2.00	0.75	0.75	0.00
32		1.38	0.50	0.88	0.50	0.00	0.00
33		1.88	0.88	0.75	0.38	0.13	0.00
AREA III	Present NEL Building						
34		1.63	0.50	0.00	0.00	1.13	0.50
35		0.25	0.00	0.00	0.00	1.00	0.50
36		0.25	0.00	0.00	0.00	1.00	0.75
37		0.50	0.00	1.25	0.00	2.00	1.25
38		0.25	0.00	1.38	0.88	2.38	2.13
39		0.00	0.00	1.63	0.63	1.63	0.38
40		0.63	1.63	2.38	1.75	1.00	0.13
41		2.13	1.63	1.88	1.50	0.25	0.13
42		2.00	1.13	2.63	1.25	0.63	0.13
43		3.00	0.88	1.88	1.25	0.63	0.13
44		3.75	0.88	2.50	1.25	1.00	0.13
45		1.25	0.00	0.13	0.00	0.38	0.00
105		0.38	0.00	0.00	0.00	1.13	0.75
106		1.13	0.38	0.00	0.00	1.38	1.13
107		1.25	1.13	0.00	0.00	2.50	1.63

STATION AREA IV Block	WINTER (NW) ORIG to NW	NEL	SUMMER (SW) ORIG	NEL	STORM (E) ORIG	NEL
46	0.88	1.00	1.50	1.13	1.63	0.88
47	0.88	1.00	0.63	1.13	1.75	1.13
48	0.38	0.38	1.50	1.25	0.88	0.88
49	0.00	0.00	0.88	0.63	0.88	0.38
50	0.88	1.00	2.38	1.63	1.50	0.88
51	2.38	1.00	2.38	1.25	1.25	0.75
AREA V TRINITY CHURCH						
52	1.38	0.50	1.13	0.50	1.00	0.25
53	0.25	0.00	1.00	1.13	0.25	0.38
54	0.50	0.25	1.75	1.13	0.75	0.13
55	0.00	0.00	1.13	0.88	0.13	0.13
56	0.00	0.00	0.50	0.50	0.00	0.00
57	0.00	0.13	0.50	0.50	0.00	0.13
58	0.63	1.13	2.00	0.75	0.88	0.88
59	0.50	0.75	1.00	1.00	0.75	2.25
60	0.50	1.63	0.38	0.88	2.38	2.25
61	1.13	1.50	2.63	1.63	2.00	1.63
62	0.88	0.63	2.75	2.00	2.13	2.13
63	1.13	0.00	2.88	1.88	0.25	0.13

STATION	WINTER (NW) ORIG	WINTER (NW) NEL	SUMMER(SW) ORIG	SUMMER(SW) NEL	STORM (E) ORIG	STORM (E) NEL
AREA VI J.H. Tower						
64	3.13	2.00	3.50	2.50	1.38	1.75
65	2.88	2.00	3.25	2.50	2.38	1.75
66	3.38	2.75	2.88	1.25	2.25	2.25
67	3.25	2.75	0.88	1.25	1.63	2.25
68	2.75	1.88	1.50	1.38	2.00	2.00
69	1.75	1.13	0.88	1.25	2.63	1.88
70	0.88	1.50	1.63	0.75	1.00	1.75
71	0.88	0.75	0.38	1.50	2.00	1.50
72	0.38	0.63	1.13	0.25	1.25	1.88
73	0.50	1.63	1.63	1.63	2.50	1.75
74	1.00	1.63	1.13	2.75	3.13	2.88
75	0.88	1.63	3.50	2.75	2.88	3.13
76	0.25	0.50	1.38	1.88	1.63	1.38
77	1.50	1.88	1.00	1.13	1.00	1.25
78	2.13	1.88	1.38	1.13	1.00	1.25

STATION	WINTER (NW) ORIG	WINTER (NW) NEL	SUMMER (SW) ORIG	SUMMER (SW) NEL	STORM (E) ORIG	STORM (E) NEL
AREA VII CLARENDON ST. BUILDING						
79	0.88	2.38	1.75	2.13	2.13	2.50
80	1.63	2.13	3.00	2.63	1.88	2.50
81	1.38	1.38	0.75	1.63	0.38	1.75
82	1.63	2.13	0.38	1.63	0.00	1.50
83	0.00	1.38	0.00	0.50	0.00	1.13
84	1.63	0.50	1.25	0.50	1.38	1.25
85	1.38	0.50	1.25	1.00	1.63	1.00
86	0.00	0.00	0.38	0.88	0.38	0.38
87	1.63	0.00	1.63	1.25	2.00	1.25
88	0.00	0.00	1.75	1.00	1.50	1.00
89	0.25	0.00	0.63	0.50	0.88	0.75
108	0.50	0.38	1.63	2.13	0.63	1.50
109	0.63	0.38	2.38	1.63	0.25	1.00
AREA VIII						
90	0.25	0.00	0.25	0.00	0.75	0.25
91	2.00	0.00	2.13	0.88	0.88	0.13
92	2.00	0.00	2.13	0.88	0.88	0.38
93	2.13	0.38	2.50	1.38	0.88	0.25
94	2.00	1.38	1.63	0.88	1.38	0.75
95	2.00	1.38	1.63	0.50	1.13	0.38
96	1.38	0.25	0.38	0.38	1.00	0.63

STATION AREA IX	WINTER (NW) ORIG	NEL	SUMMER (SW) ORIG	NEL	STORM (E) ORIG	NEL
Block to E						
97	0.00	0.00	1.13	0.75	1.38	0.50
98	1.38	1.88	2.25	0.50	1.13	0.38
99	1.38	2.38	2.25	0.50	0.88	0.63
100	1.75	1.88	1.00	0.25	0.50	0.38
101	0.75	0.50	0.00	0.00	0.00	0.00
102	0.75	1.25	0.75	0.63	1.25	0.13
103	0.75	0.75	0.50	0.00	1.25	0.00
104	0.25	0.00	0.00	0.00	0.50	0.00

Table 4. Summary of Numbers of Scores that Exceed Indicated Value

ORIGINAL — WINTER

AREA	>0.0	>1.0	>1.5	>2.0	>2.5	>3.0	>3.5	>4.0
I	20 + 8	2	0	0	0	0	0	0
II	5	4	3	2	0	0	0	0
III	15	8	5	3	2	1	1	0
IV	6	1	1	1	0	0	0	0
V	12	3	0	0	0	0	0	0
VI	15	8	7	6	5	3	0	0
VII	13	6	4	0	0	0	0	0
VIII	7	6	5	1	0	0	0	0
IX	8	3	1	0	0	0	0	0
	TOTALS							
	101	41	26	13	7	4	1	0

ORIGINAL — SUMMER

AREA	>0.0	>1.0	>1.5	>2.0	>2.5	>3.0	>3.5	>4.0
I	20 + 8	7	5	2	2	0	0	0
II	5	3	3	1	0	0	0	0
III	15	8	6	3	1	0	0	0
IV	6	4	2	2	0	0	0	0
V	12	7	5	3	3	0	0	0
VI	15	11	6	4	4	3	0	0
VII	13	8	6	2	1	0	0	0
VIII	7	5	5	3	0	0	0	0
IX	8	3	2	2	0	0	0	0
	TOTALS							
	101	56	40	22	11	3	0	0

ORIGINAL — STORM

AREA	>0.0	>1.0	>1.5	>2.0	>2.5	>3.0	>3.5	>4.0
I	20 + 8	2	1	0	0	0	0	0
II	5	0	0	0	0	0	0	0
III	15	7	4	2	0	0	0	0
IV	6	4	2	0	0	0	0	0
V	12	3	3	2	0	0	0	0
VI	15	12	10	6	3	1	0	0
VII	13	6	4	1	0	0	0	0
VIII	7	2	0	0	0	0	0	0
IX	8	4	0	0	0	0	0	0
	TOTALS							
	101	40	24	11	3	1	0	0

ORIGINAL — ALL SEASONS

AREA	>0.0	>1.0	>1.5	>2.0	>2.5	>3.0	>3.5	>4.0
I	60	11	6	2	2	0	0	0
II	15	7	6	3	0	0	0	0
III	45	23	15	8	3	1	1	0
IV	18	9	5	3	0	0	0	0
V	36	13	9	5	3	0	0	0
VI	45	31	23	16	12	7	0	0
VII	39	20	14	3	1	0	0	0
VIII	21	13	10	4	0	0	0	0
IX	24	10	5	2	0	0	0	0
	TOTALS							
	303	137	90	46	21	9	1	0

NKL — WINTER

AREA	>0.0	>1.0	>1.5	>2.0	>2.5	>3.0	>3.5	>4.0
I	20 + 8	2	0	0	0	0	0	0
II	5	0	0	0	0	0	0	0
III	15	4	2	0	0	0	0	0
IV	6	0	0	0	0	0	0	0
V	12	3	1	0	0	0	0	0
VI	15	12	10	2	2	0	0	0
VII	13	55	3	3	0	0	0	0
VIII	7	2	0	0	0	0	0	0
IX	8	4	3	1	0	0	0	0
	TOTALS							
	109	32	19	6	2	0	0	0

NKL — SUMMER

AREA	>0.0	>1.0	>1.5	>2.0	>2.5	>3.0	>3.5	>4.0
I	20 + 8	2	0	0	0	0	0	0
II	5	0	0	0	0	0	0	0
III	15	5	1	0	0	0	0	0
IV	6	5	1	0	0	0	0	0
V	12	5	3	0	0	0	0	0
VI	15	13	5	4	2	0	0	0
VII	13	7	6	3	1	0	0	0
VIII	7	1	0	0	0	0	0	0
IX	8	0	0	0	0	0	0	0
	TOTALS							
	109	38	17	7	3	0	0	0

NKL — STORM

AREA	>0.0	>1.0	>1.5	>2.0	>2.5	>3.0	>3.5	>4.0
I	20 + 8	1	0	0	0	0	0	0
II	5	0	0	0	0	0	0	0
III	15	4	2	1	0	0	0	0
IV	6	1	0	0	0	0	0	0
V	12	4	4	3	0	0	0	0
VI	15	15	11	4	2	1	0	0
VII	13	8	3	2	0	0	0	0
VIII	7	0	0	0	0	0	0	0
IX	8	0	0	0	0	0	0	0
	TOTALS							
	109	33	20	10	2	1	0	0

NKL — ALL SEASONS

AREA	>0.0	>1.0	>1.5	>2.0	>2.5	>3.0	>3.5	>4.0
I	94	5	0	0	0	0	0	0
II	15	0	0	0	0	0	0	0
III	49	13	5	1	0	0	0	0
IV	18	6	1	0	0	0	0	0
V	36	12	8	3	0	0	0	0
VI	45	40	27	10	6	1	0	0
VII	39	20	12	9	1	0	0	0
VIII	21	3	0	0	0	0	0	0
IX	24	4	3	1	0	0	0	0
	TOTALS							
	327	103	56	23	7	1	0	0

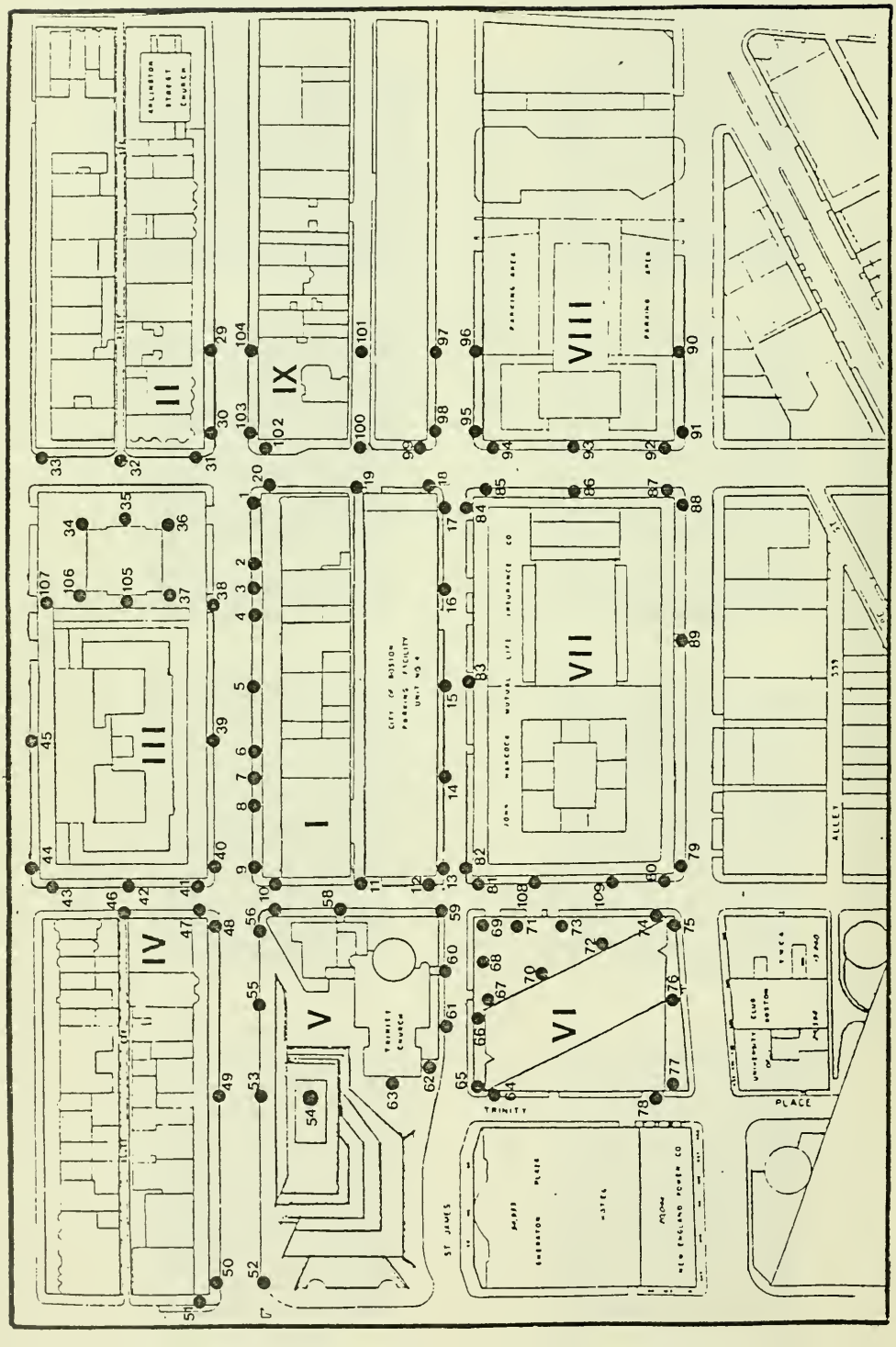

FIGURE 1. MAP OF TEST AREA AND LOCATIONS OF GROUND WIND STATIONS
EXISTING CONDITIONS

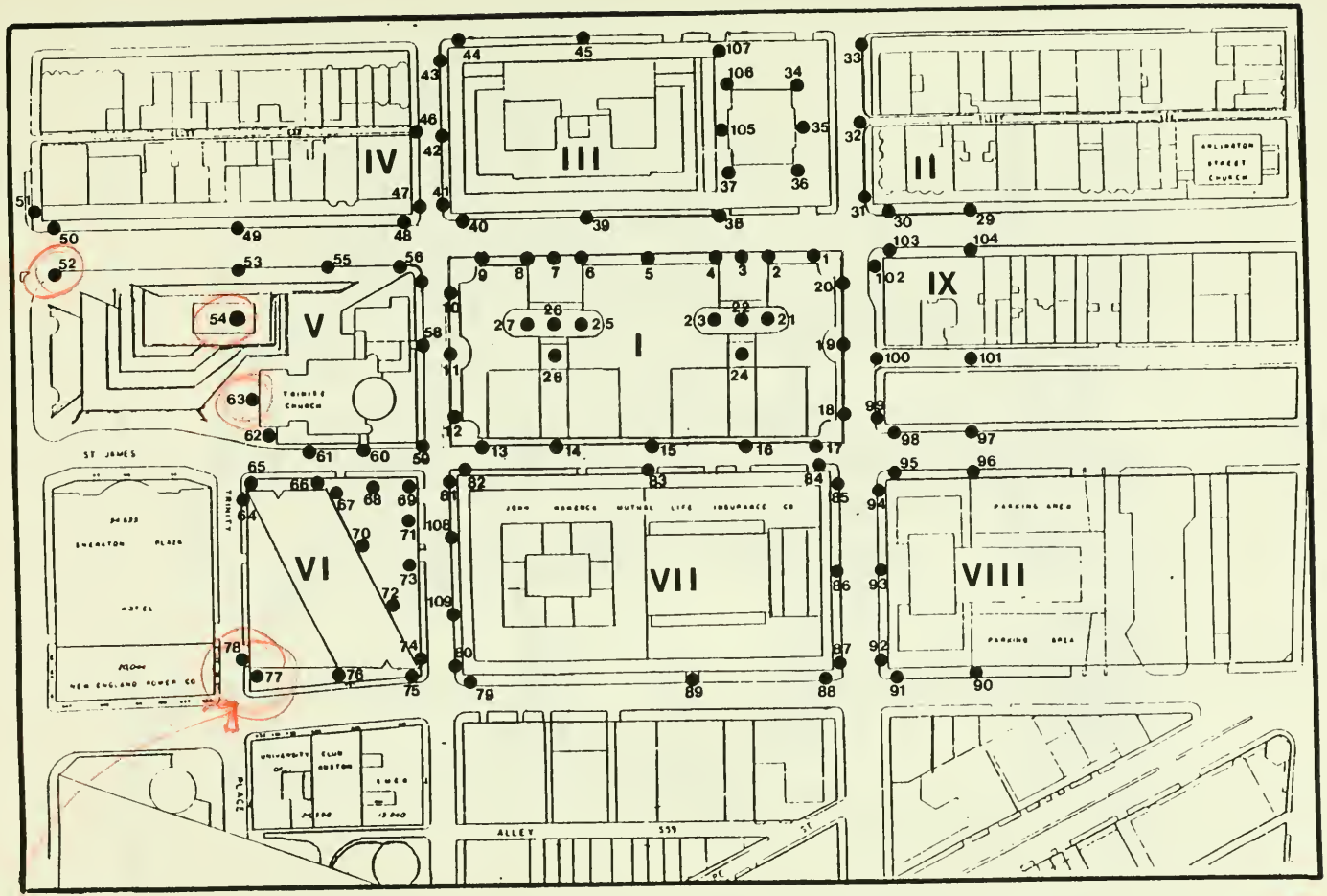

FIGURE 2. MAP OF TEST AREA AND LOCATIONS OF GROUND WIND STATIONS-
WITH PROPOSED NEL BUILDING

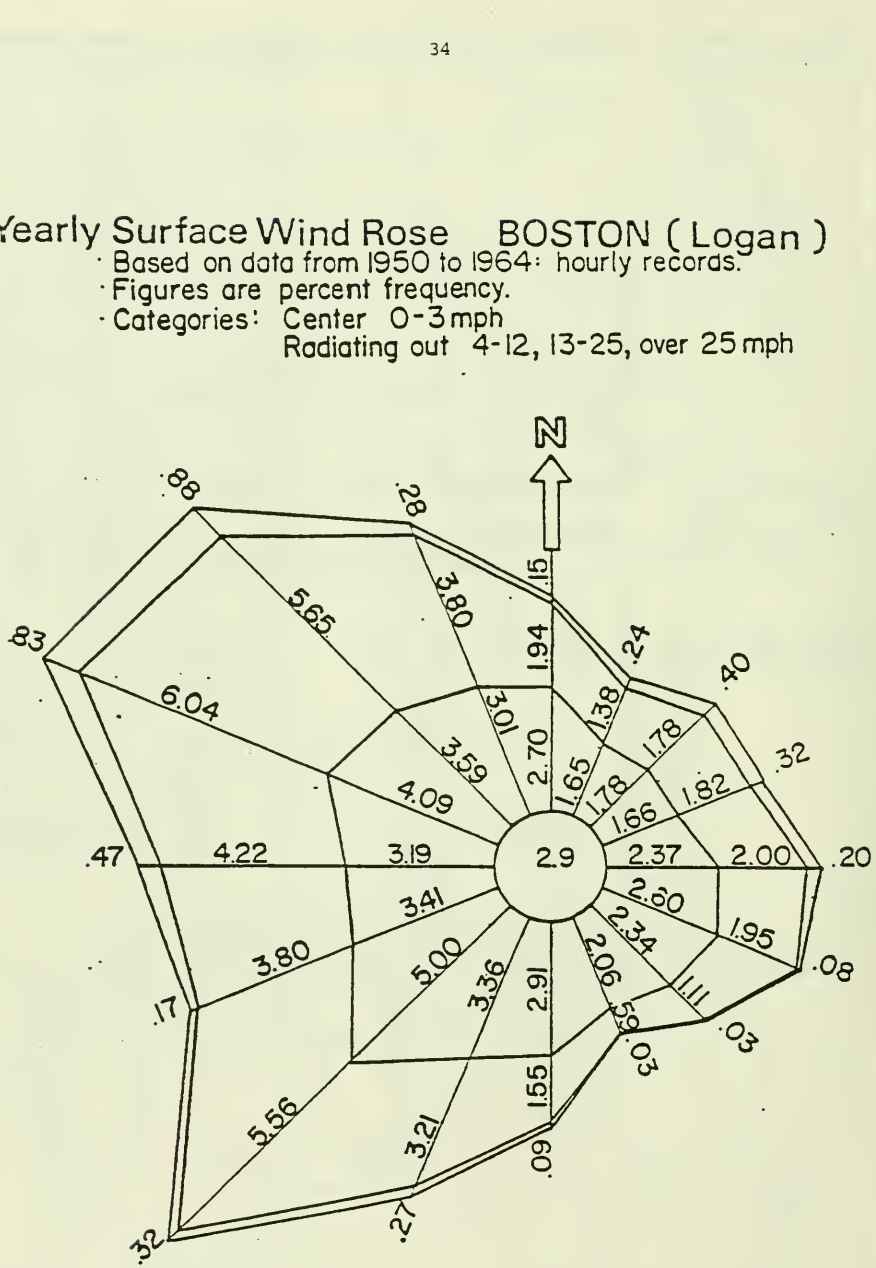

Figure 3. Wind rose for Boston

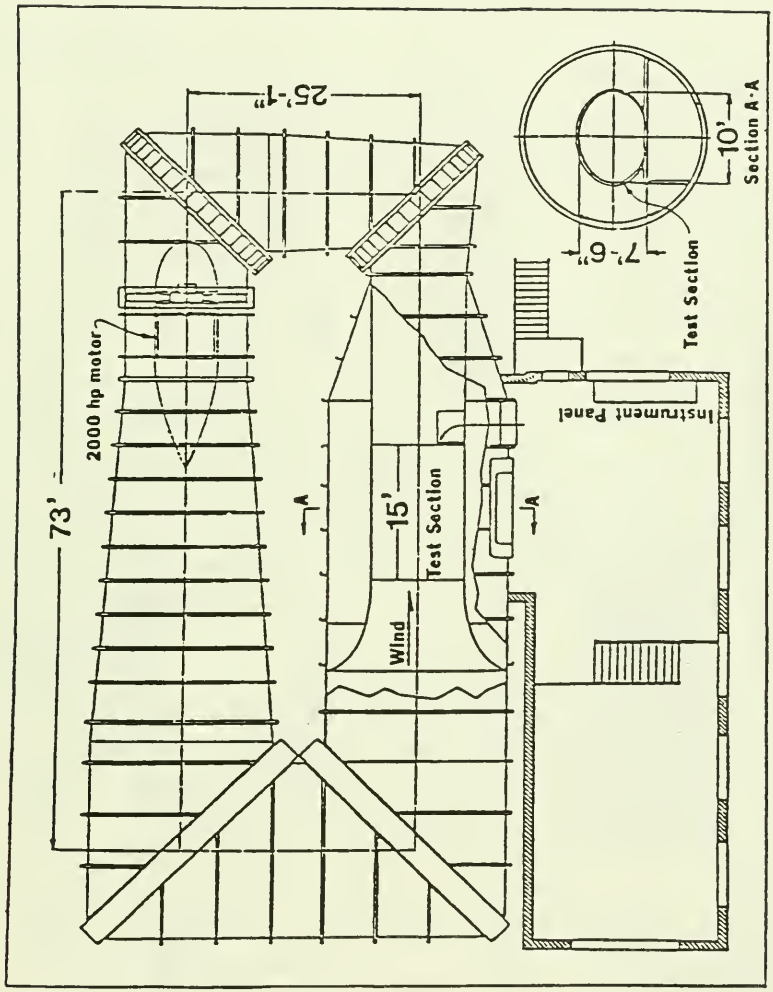

FIGURE 4. Schematic diagram of Wright Brothers wind tunnel (WBWT)

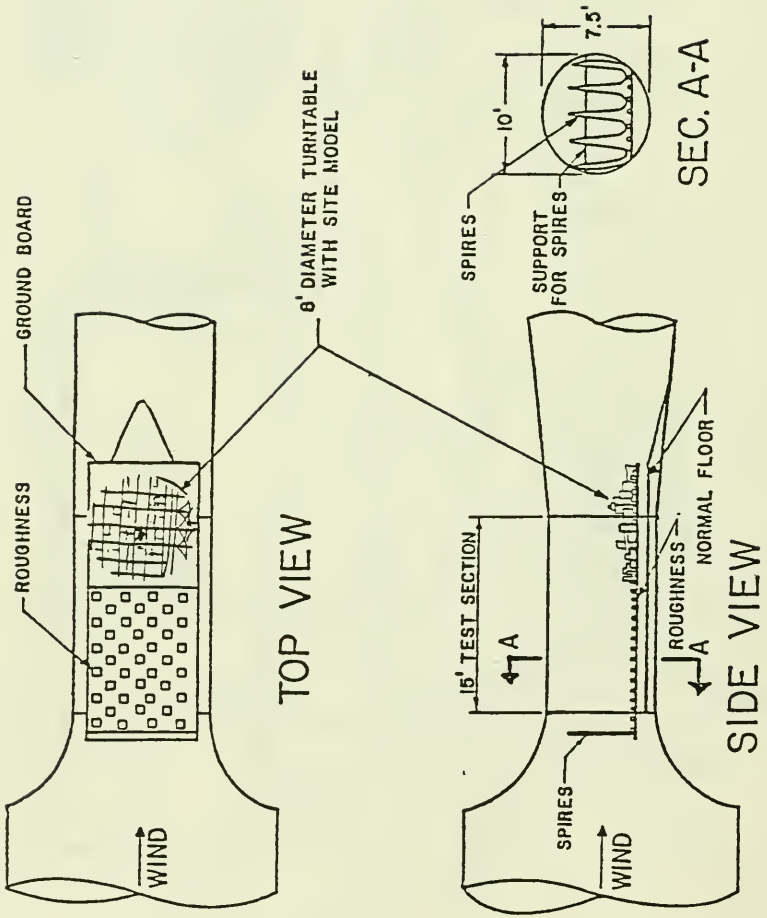

FIGURE 5. Schematic diagram of boundary layer simulation in the WBWT

APPENDIX A

Experimental Equipment

1. The Wind Tunnel

The Wright Brothers Facility is a closed return wind tunnel with a 7.5 x 10.0 foot elliptical test section approximately 15 feet long (see Figure 4). Wind speeds up to 185 mph are currently available.

For non-aeronautical tests such as represented by this study, a special floor is mounted one foot above the regular floor of the tunnel, extending from two feet into the contraction section to four feet into the diffuser. This "ground board" provides a flat plane on which to develop a simulated Earth's boundary layer. An eight-foot diameter turntable is mounted flush with the ground board in order to rotate the model to simulate wind from all directions. The center of the turntable is 15 feet from the leading edge of the ground board (see Figure 5).

A "scaled" Earth's boundary layer was developed in the wind tunnel using spires installed near the leading edge of the ground board, and roughness blocks $1\frac{1}{2}$ inches square and 2 inches high distributed between the spires and turntable along the flow direction. The calibration of this flow is described in Appendix B.

2. The Models

Three different models were tested in this study. Each consisted of a model of the proposed New England Life complex or the existing buildings in the block surrounded by a common area model which modeled all buildings out to about 2000 feet from the NEL block. The model used in the original test of the NEL site with the existing buildings did not include the Trinity Church Parish House, so this test was partially repeated with Trinity Church correctly modeled.

The model scale for the test was chosen to be 1-600 and was determined by three factors:

1. Consistency with the Earth's boundary layer simulation was required.

2. Tunnel blockage with respect to the cross-sectional area must be small (<5%).

3. A sufficient area coverage surrounding the NEL building was to be provided such that at least three (3) feet (600-1200 feet full scale) was modeled between any area of interest and the edge of the model.

For the wind erosion technique, plastic particles were placed on the ground surface of the model. The areas from which the particles were blown away as the wind speed was increased are recorded photographically, using two Olympus OM-1 SLR cameras with an automatic rewind mounted about one foot apart 6 feet directly over the center of the turntable. Two cameras were used because typically the taller buildings obscured certain areas from the view of one of the cameras. A screen 18 inches high was installed behind the turntable to catch the granules of plastic as they were swept downstream of the model by the air flow. The granules were saved for later reuse. The average size of an individual granule was approximately 1 x 1 x 2 mm, and in the bulk there are between 195-200 particles per gram.

The tunnel gradient velocity (the uniform or constant velocity in the wind tunnel above both the simulated Earth's boundary layer and the model, and the velocity used for all the data tables) was measured 15 inches below the tunnel ceiling and directly above the model of the proposed New England Life complex.

APPENDIX B

Wind Tunnel Flow Calibration

1. Introduction

Proper wind tunnel simulation of the Earth's atmospheric boundary layer requires careful consideration of the significant scaling relationships. The parameters in wind tunnel-to-full scale simulation are (1) velocity gradient, (2) longitudinal root-mean-squared (RMS) turbulence fluctuation, and (3) longitudinal velocity power spectrum. Scaling on the basis of these parameters represents state-of-the-art methods in wind tunnel testing of ground structures. Each of these parameters and the similarity relation for sampling times are discussed in the following.

2. Velocity Gradient Simulation

The velocity gradient, or velocity variation with height, can be simulated readily (Epstein [11]). Davenport [5,6] states that while other more sophisticated approximations exist to the vertical velocity gradient of the Earth's boundary layer, the overall accuracy is not significantly better than the simple approximation:

$$\frac{U}{U_g} = \left(\frac{h}{h_G}\right)^{\alpha} \tag{B-1}$$

where

U = average wind velocity at height h

U_g = average wind velocity at gradient height h_g

α = power law constant, typically varies from 0.14 to 0.45

Davenport [6] shows that h_G and α vary approximately with the terrain, as given in Table B1. These parameters and their appropriate terrains are depicted in Figure B.1.

The boundary layer used for these tests had values equivalent to $\alpha = 0.25$ and $h_G = 1675$ feet full scale. The terrain of the area surrounding the modeled portion of Boston can be classified as built-up suburban and low-rise industrial. Taking this terrain into consideration, an $\alpha = 0.25$ is believed to approximate the local velocity gradient reasonably well. It must be remembered that the values for α and h_G presented in Table B.1.

are guidelines and are representative of the velocity gradients that Davenport suggests from his surveys of experimental results. These values cannot be expected to agree exactly with any other site. For a review of the variations that have been found by other authors at other sites, see the article by Counihan [4].

The gradient height modeled in the wind tunnel for $\alpha = 0.25$ was 1675 feet. Fig.B.2a depicts the averaged modeled velocity gradient measured at the center and one foot to either side of the center of the turntable.

3. Longitudinal Turbulence Intensity

Longitudinal turbulence intensity is a measure of the root-mean-squared (RMS) velocity variation about the average velocity. In Fig.B.2b the ratio of longitudinal turbulence intensity to gradient wind velocity is compared with actual wind data. This ratio was measured in the wind tunnel as a function of height above the floor. The values are compared with strong wind data from Brookhaven, USA, and Sale, Australia, as presented in Campbell and Standen [2].

Brookhaven is considered typical of suburban areas and so Campbell and Standen [2] have assumed parameters of exponent $\alpha = 0.28$ and height h_G = 1300 feet. Sale is considered to represent open terrain and has been assigned $\alpha = 0.16$ and h_G = 900 feet. These values appear to have been selected directly from Davenport's results, which were given earlier in Table B.1. In a later publication, Counihan [4] presents values of $\alpha = 0.21$ to 0.33 for Brookhaven and $\alpha = 0.16$ to 0.176 for Sale. These have been compiled from various authors published since 1955. The scatter in the values is probably reasonable, since it is unlikely that any of the data was taken in truly adiabatic conditions. Thus a comparison of controlled wind tunnel turbulence intensity to atmospheric conditions must be interpreted for general, not exact, agreement.

For the NEL site, the turbulence intensity in the wind tunnel falls within the scatter of Brookhaven and Sale. The wind tunnel turbulence data shown were taken with a gradient wind speed of about 60 mph.

4. Power Spectral Density

The power spectrum of the longitudinal velocity component for the simulated flow described above was deduced with the aid of program TWOSPC [14] operating on the WBF PDP 11-20 computer. The program samples the wind velocity at a

specified sampling rate, passes the data through a fast Fourier transform, and outputs the values of the power spectrum. Data was taken at 12 inches above the wind tunnel floor, corresponding to 600 feet full scale. The power spectrum is shown in Figure B.2C. The shape of the spectrum shown is in reasonable agreement with the empirical strong wind spectrum proposed by Davenport [6] and the more theoretical spectrum of Von Karman (Epstein [11]). Davenport's spectrum is defined by:

$$\frac{nS(n)}{\sigma^2} = \frac{2}{3}\frac{X^2}{(1+X^2)^{4/3}} \tag{B-2}$$

Von Karman's spectrum is defined by:

$$\frac{nS(n)}{\sigma^2} = \frac{2}{\pi}\frac{X_v}{(1+X_v^2)^{5/6}} \tag{B-3}$$

where

$X = nL/U_{33}$

$X_v = \left(2\pi n \ell x/U_g\right)\left(\sqrt{1.8}\right)$

$S(n)$ = power spectral density function

n = frequency

U_{33} = average wind velocity at 33 feet above ground surface

L = 3000 feet

ℓx = 500 feet

σ = RMS of fluctuating wind velocity

According to Davenport [6], the power spectral density function is independent of height for much of the boundary layer height. Wind velocity is a function of height, h. To convert n/U_{33} full scale to n/u_1 in the tunnel (u_1 is the average wind velocity at 1 foot above the floor of the tunnel), the following relationship is used:

$$\left(\frac{n}{u_1}\right) = m\left(\frac{33}{m}\right)^{\alpha}\left(\frac{n}{U_{33}}\right) \tag{B-4}$$

where m is the reciprocal of the scale factor and α is the velocity gradient power law constant. In this test, m = 600 and α = 0.25

Table B.1 Gradient Heights and Power Law Exponents for Various Terrains, after Davenport [5,6]

Terrain Types	Gradient Height h_G (feet)	Exponent, α
Open field or water	900	0.16
Wooded and suburban areas	1300	0.28
Built-up urban areas	1700	0.40

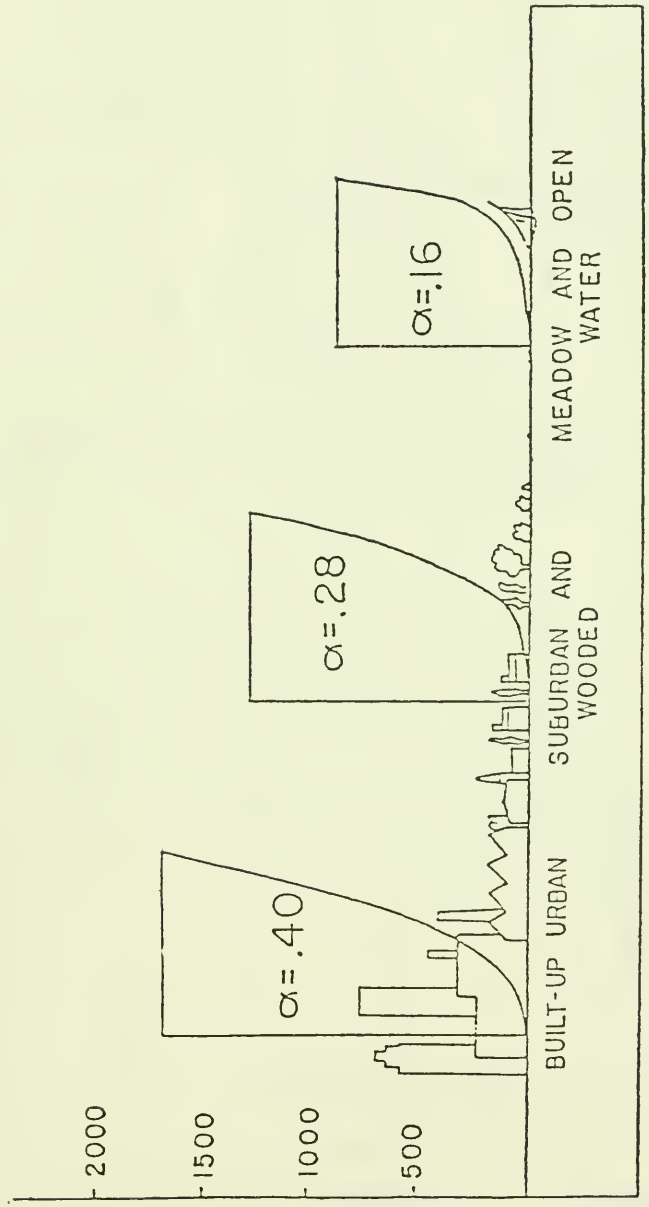

Figure B.1 Typical power law profiles for various terrain

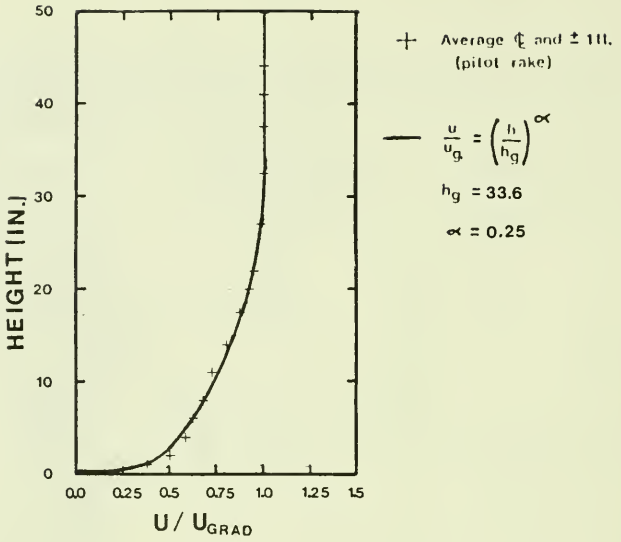

FIGURE B.2a BOUNDARY LAYER PARAMETERS, AVERAGE VELOCITY VS HEIGHT

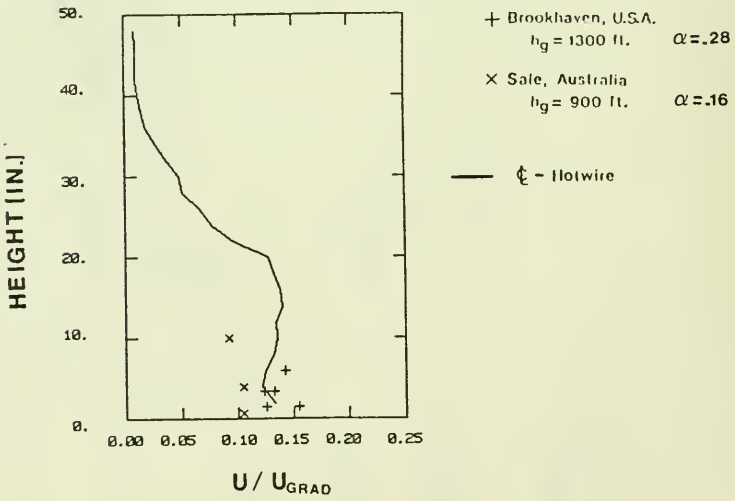

FIGURE B.2b RMS VELOCITY VS HEIGHT

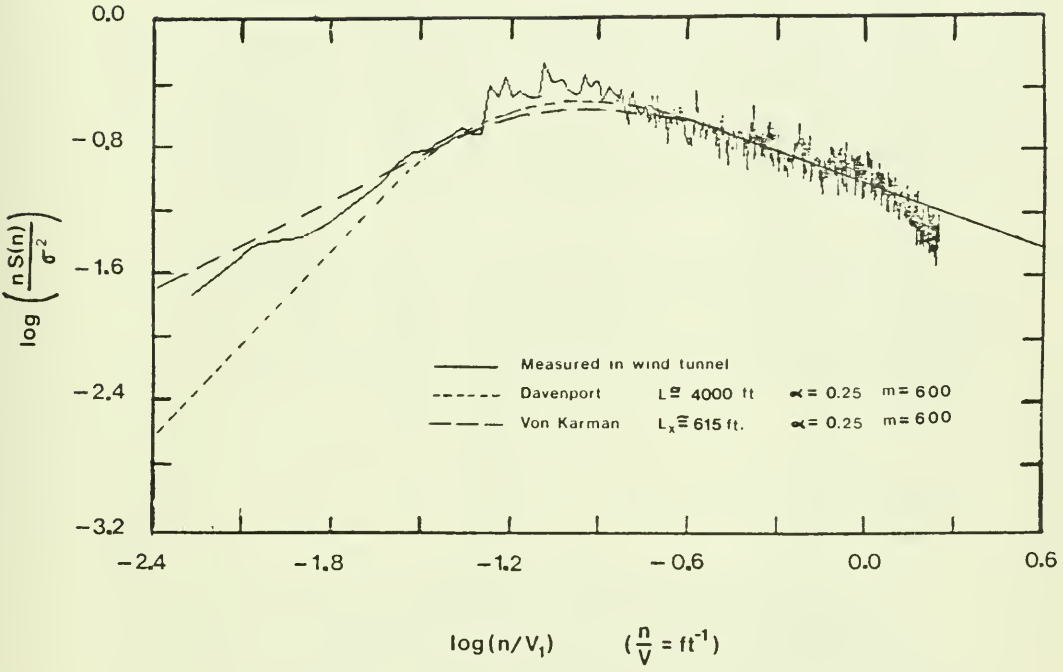

Figure B-2C. Power spectral density of longitudinal velocity at 1 foot in the wind tunnel

APPENDIX C

Experimental Procedure - Wind Erosion Technique

Spires and roughness blocks which provide a flow simulating the Earth's boundary layer were installed in the tunnel test section and the boundary layer flow was calibrated. The layer that was generated had a depth of 33.5 inches and a power law exponent equal to 0.25 (Appendix D). The longitudinal turbulence intensity was about 14 percent referenced to gradient velocity, and the gust scales were such that they matched Davenport's spectrum [6] at a scale of about 1-600.

The unreduced data for this test is in the form of a series of photographs showing the distribution of particles for different gradient velocities and wind directions. A typical photograph is shown in Figure C.1. To generate the data, plastic granules were sprinkled one layer thick on the ground surface of the model. The gradient velocity of the tunnel was then increased to no more than 15 mph (the first test speed here). After a period of 20 to 30 seconds at constant speed to allow the granule distribution to stabilize, photographs were taken using two cameras mounted directly above the center of the test section turntable. Two cameras were used in these tests in order to minimize the area blocked out by tall buildings. The gradient velocity was then increased to the next test speed, 20 mph, and after a second stabilization period of 20 to 30 seconds the photographs were repeated. The procedure was repeated again for each gradient velocity of 25, 30, 35, and 40 mph. After photographing the results at the maximum test speed, the gradient velocity was reduced to zero, the turntable was rotated to a new compass direction, and the particles vacuumed off the model. A one layer thick distribution on the ground surface of the model was then repeated before the procedure was again carried out for a different wind direction.

In a recent study, Grip [12] has investigated the relationship between the velocities indicated on using an erosion technique and as measured by a hot-wire anemometer. He found that the erosion technique tends to indicate peak velocities and that it was not possible to find a simple relationship between the two types of data because the two methods measure the wind

velocity at two different heights above the ground. Indeed, the wind erosion technique tends to overestimate the high velocity areas and thus can be used to obtain qualitative information about the wind environment.

GRADIENT VELOCITY = 0 MPH

GRADIENT VELOCITY = 40 MPH

FIGURE C.1 TYPICAL PHOTOGRAPH OF PARTICLE EROSION

APPENDIX D

The Scoring System

The scoring system allows one to assign a relative score for each station for summer, winter and storm periods. Such average scores are defined as follows:

$$\text{Summer (SW) Average} = \frac{1}{4}\left(\frac{1}{2}\,S + SSW + SW + WSW + \frac{1}{2}\,W\right) \qquad (D\text{-}1)$$

$$\text{Winter (NW) Average} = \frac{1}{4}\left(\frac{1}{2}\,N + NNW + NW + WNW + \frac{1}{2}\,W\right) \qquad (D\text{-}2)$$

$$\text{Storm (E) Average} = \frac{1}{4}\left(\frac{1}{2}\,N + NE + E + SE + \frac{1}{2}\,S\right) \qquad (D\text{-}3)$$

where S, SSW, ... are the scores derived from Tables 1 and 2. Effectively these are average scores for the wind directions covered in each case.

This scoring system provides a systematic basis for evaluating each station on the model with respect to all others and an established windiness criteria.

Grip has shown that the wind velocity which causes a particle to move is approximately constant at the particle (the velocity does vary somewhat with local wind direction and gradient). We will refer to that velocity as U_{ero}.

A basic assumption of both the hot wire and erosion tests is that the ratio of the actual velocity (U) at any station on the model to the gradient velocity, U_{grad}, in the wind tunnel is independent of the gradient velocity. The actual velocity at any station is affected by the gradient wind velocity, its direction and all of the nearby buildings. Thus the ratio of the actual velocity at a station when the particles first move to gradient velocity is U_{ero}/U_{grad}. This is a measure of $U/U_{gradient}$ at that station, and as stated above this ratio is independent of gradient velocity. In general a large value of $U/U_{gradient}$ at a station implies that the winds are stronger there. Thus the first station for which the particles blow completely away is probably the windiest station for that wind direction.

It is important to note that the particles actually are blown away by the strongest gust rather than the average wind. Also, a typical hot wire study uses the average wind and not the peak gust. In this sense the hot wire and erosion studies are effectively measuring two different things - average and peak gust winds respectively.

but there no reason why it can't be used to

In many hot wire studies an effective peak velocity defined as

$$U_{eff} = U_{ave} + g\, U_{rms} \qquad \text{(D-4)}$$

is frequently used in order to account for the gusting. Values in the range 1.0-3.5 have been suggested. However, examination of any hot wire data (3,8,9) shows that if U_{eff} is to be the peak gust, then g can vary from 2.0-28. Thus U_{eff} is not a peak gust, but simply a modified average.

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